Super Ball Bot - Structures for Planetary Landing and Exploration

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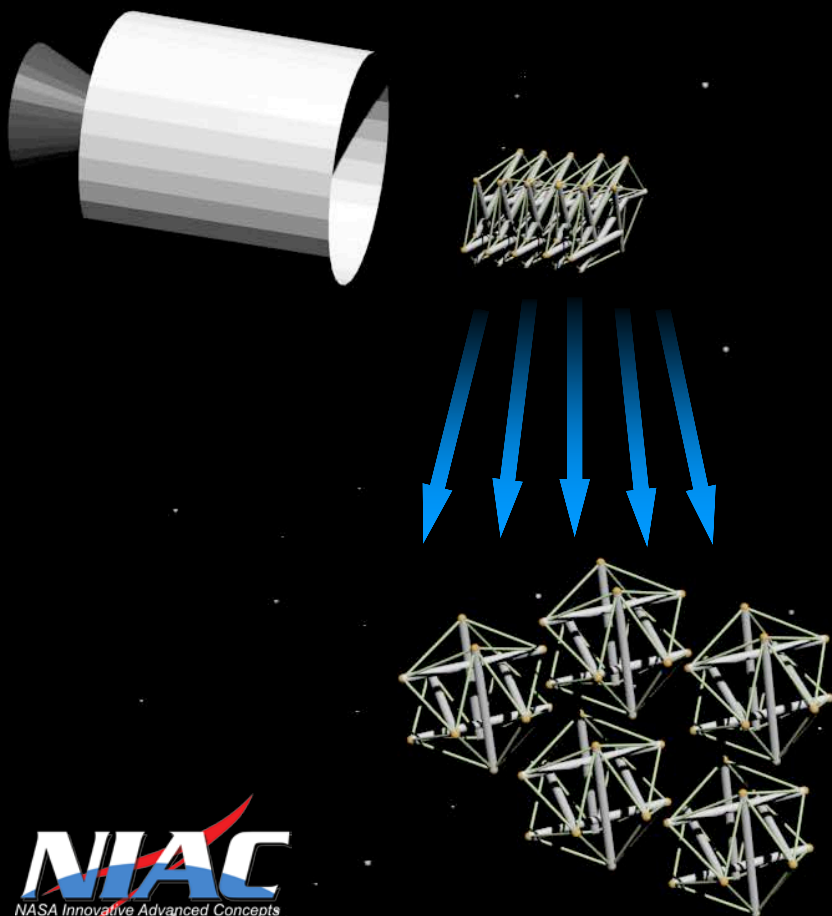
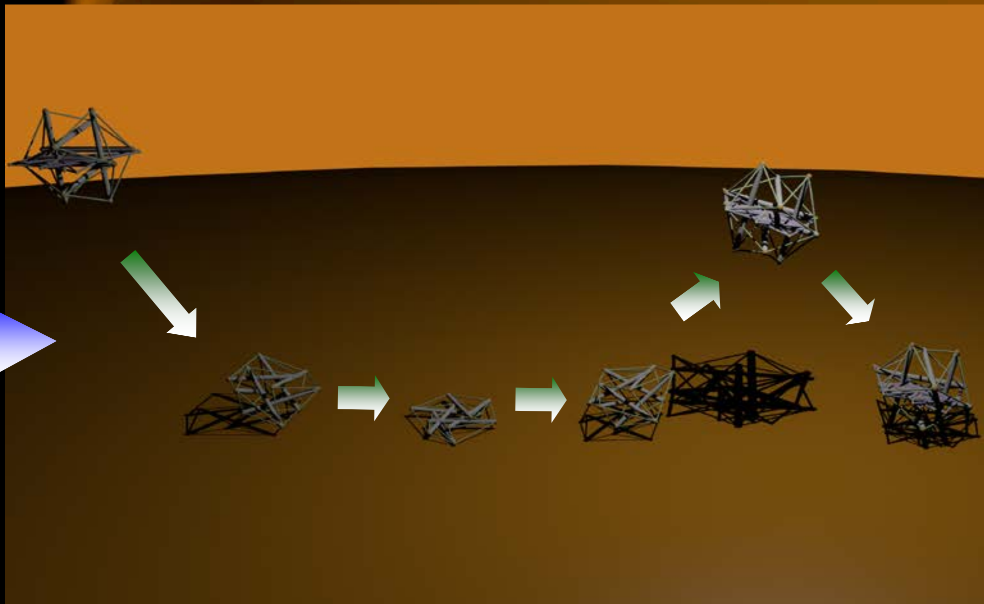
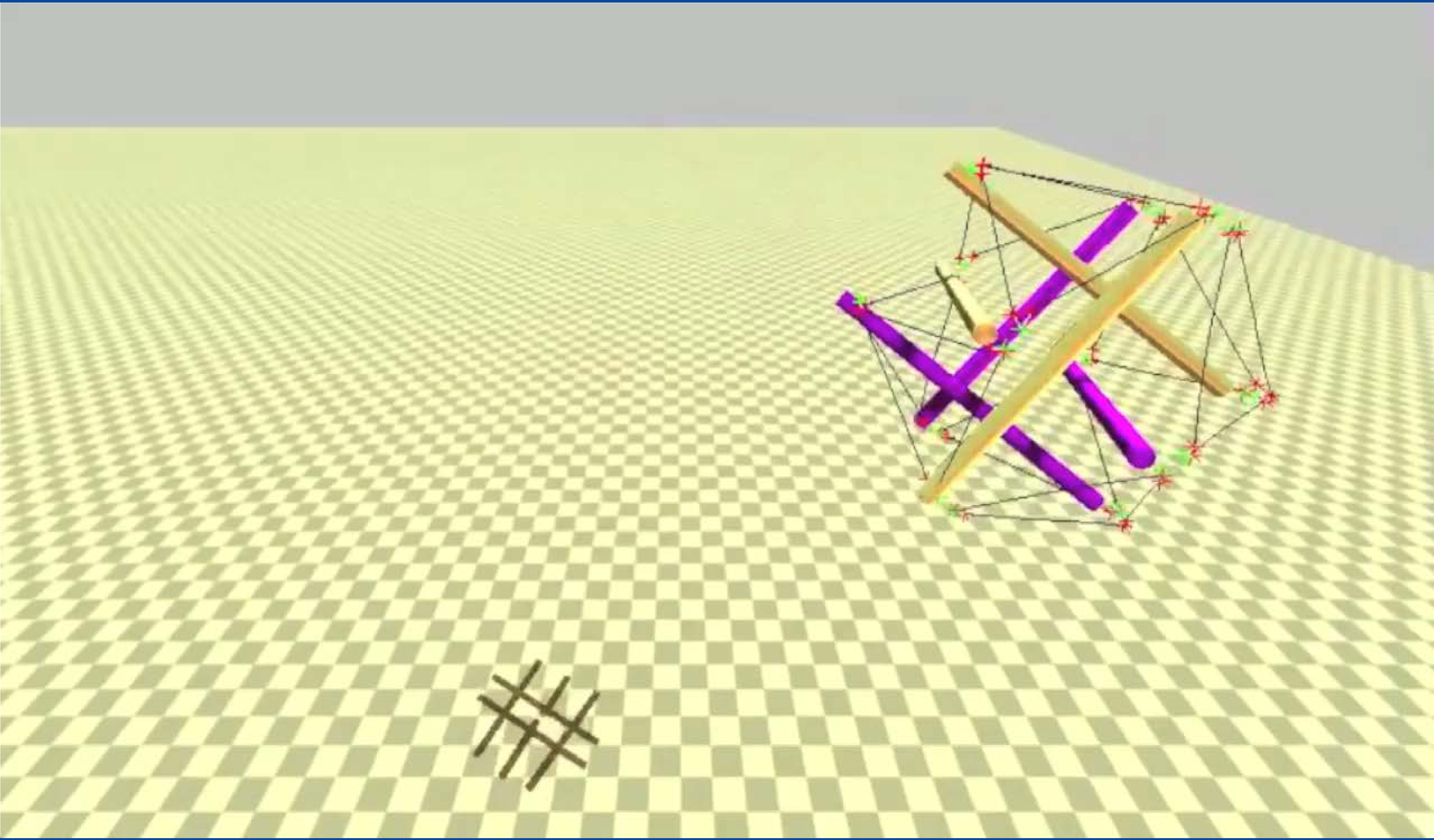


NASA Ames Research Center (ARC)
Intelligent Systems Division (Code TI)
Intelligent Robotics Group (IRG)
Robust Software Engineering (RSE)



NIAC
NASA Innovative Advanced Concepts

Super Ball Bot – Landing and Mobility

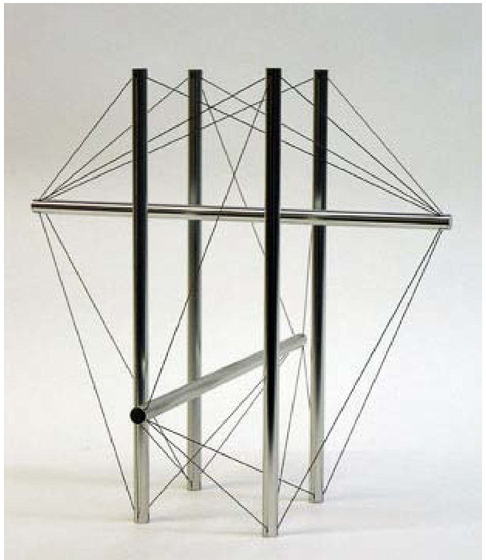


Outline

- **Tensegrity Robots**
- **Titan Reference Mission**
- **Engineering for EDL**
- **Engineering for Mobility**
- **Controls for Mobility**
- **Collaborations & Papers**
- **Future Work**

Tensegrity

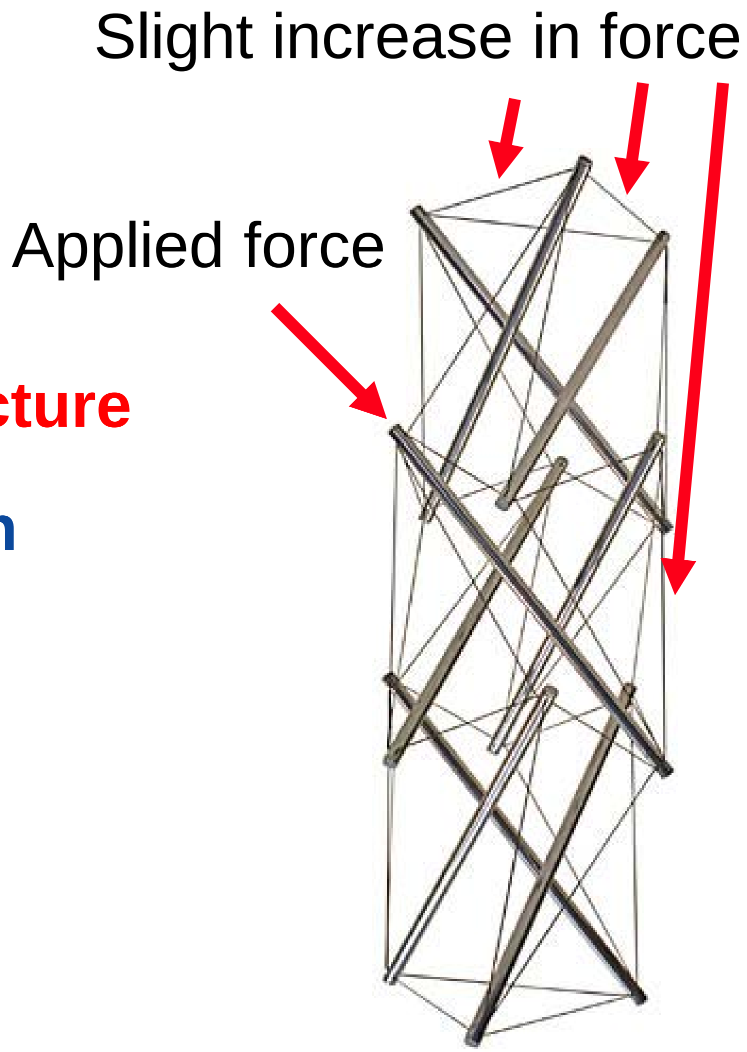
- **First explored by Kennith Snelson in 1960's**

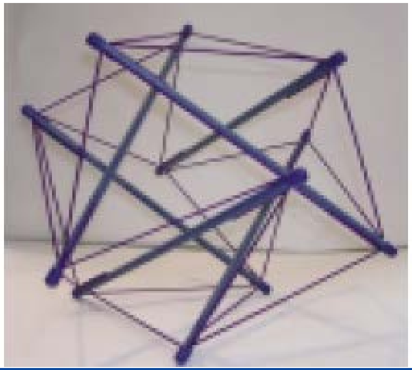


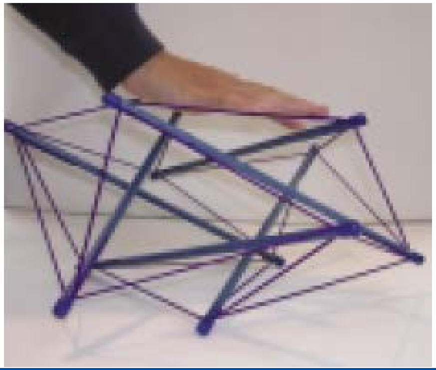
Named by Buckminster Fuller: "Tension" + "Structural Integrity"

Tensegrity Force Distribution Properties

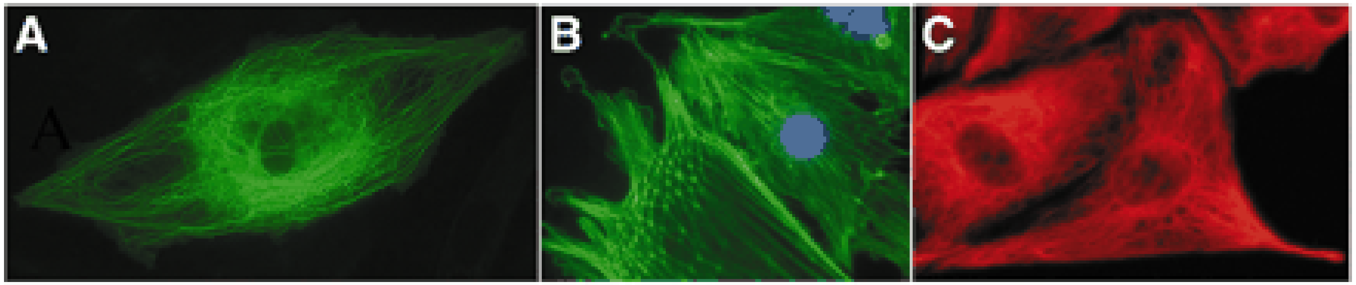
- **Global Force Distribution**
- **Minimize points of local weakness**
- **No lever arms to magnify forces**
- **Maximum Strength to Weight Structure**
- **Pure Tension or Pure Compression**



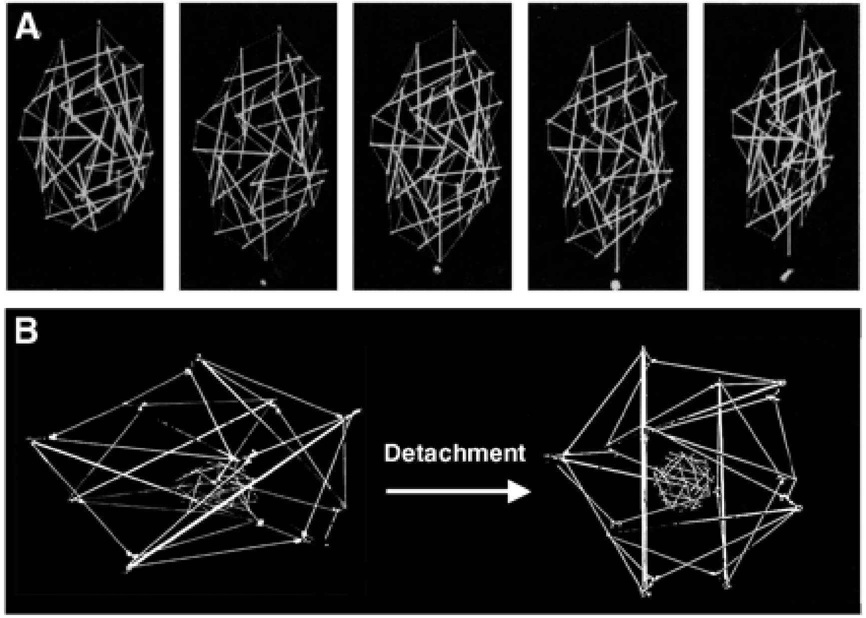




Donald Ingber & Cellular Tensegrity



Microtubules, microfilaments and intermediate filaments within the cytoskeleton of endothelial cells



Biotensegrity – Tension model of body.

Steve Levin Initiated Research into “Biotensegrity”

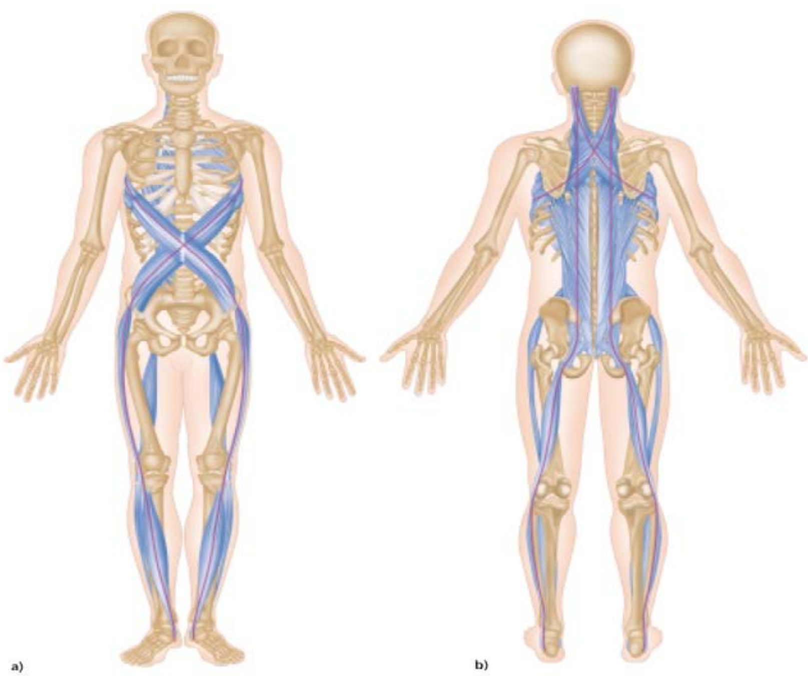


Figure 8.16: The Spiral Line (SL); a) anterior view, b) posterior view.

From “Anatomy Trains” by
Tom Meyers

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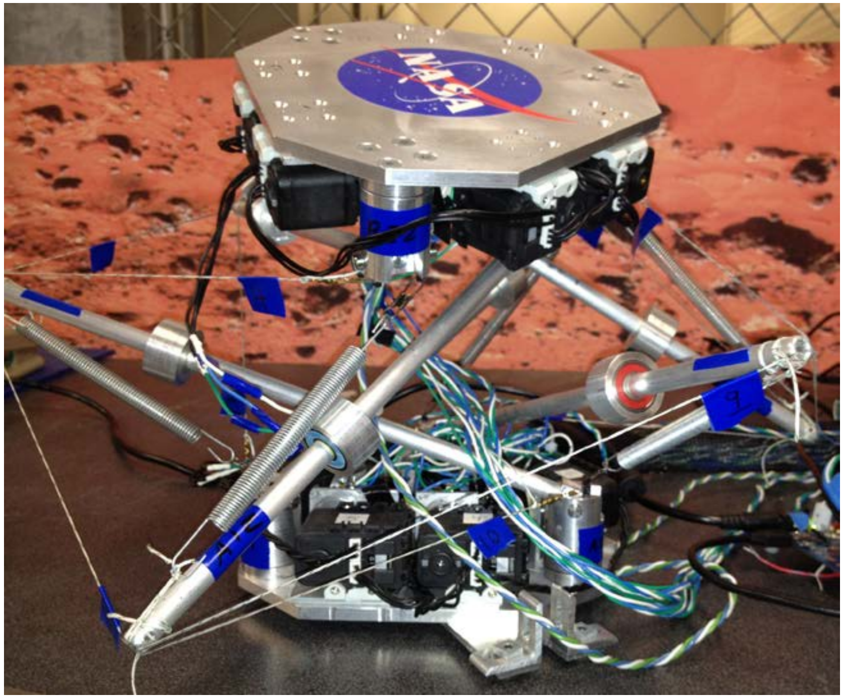
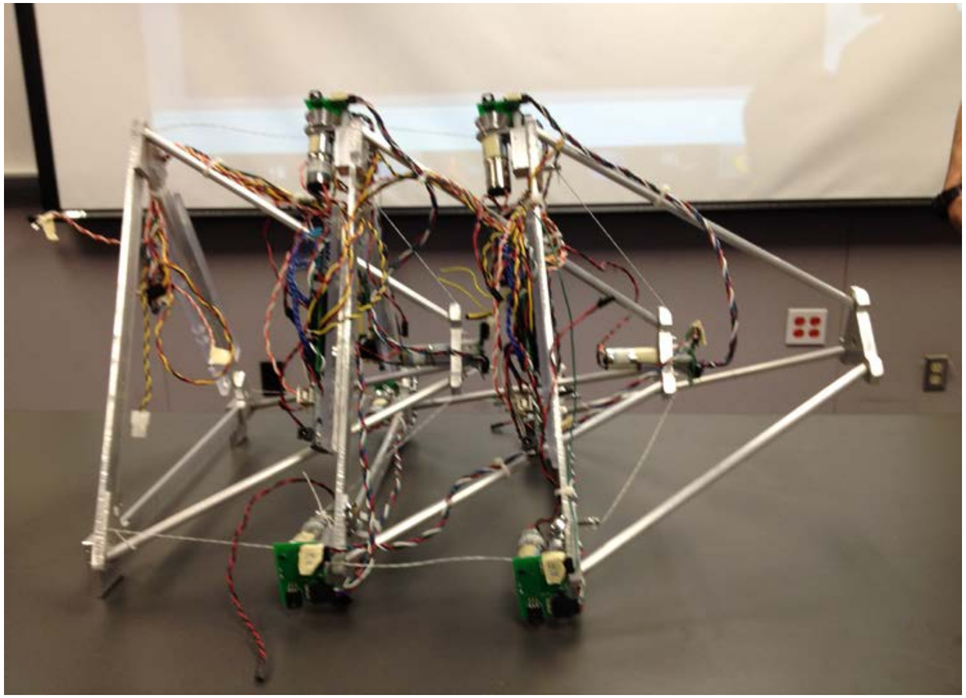
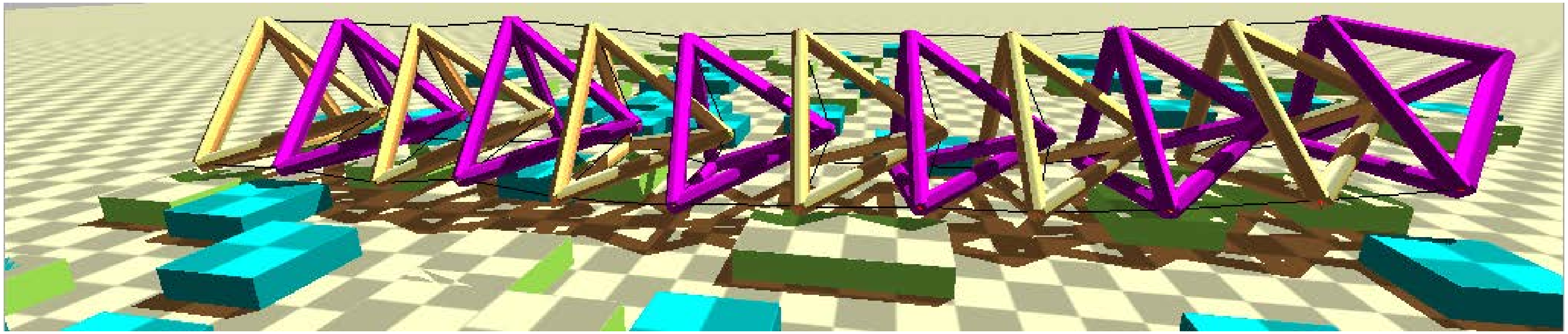
Building Prototypes and Simulations of Tensegrity Robots







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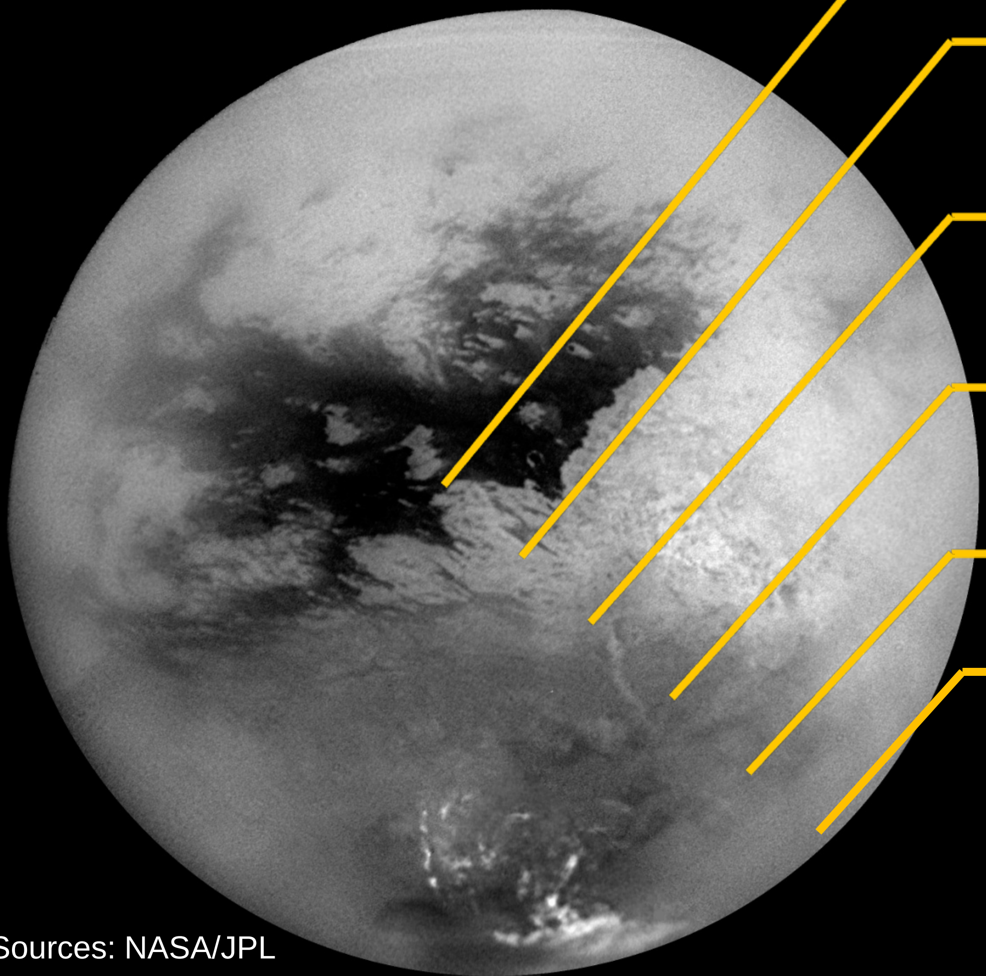
Titan Science Objectives

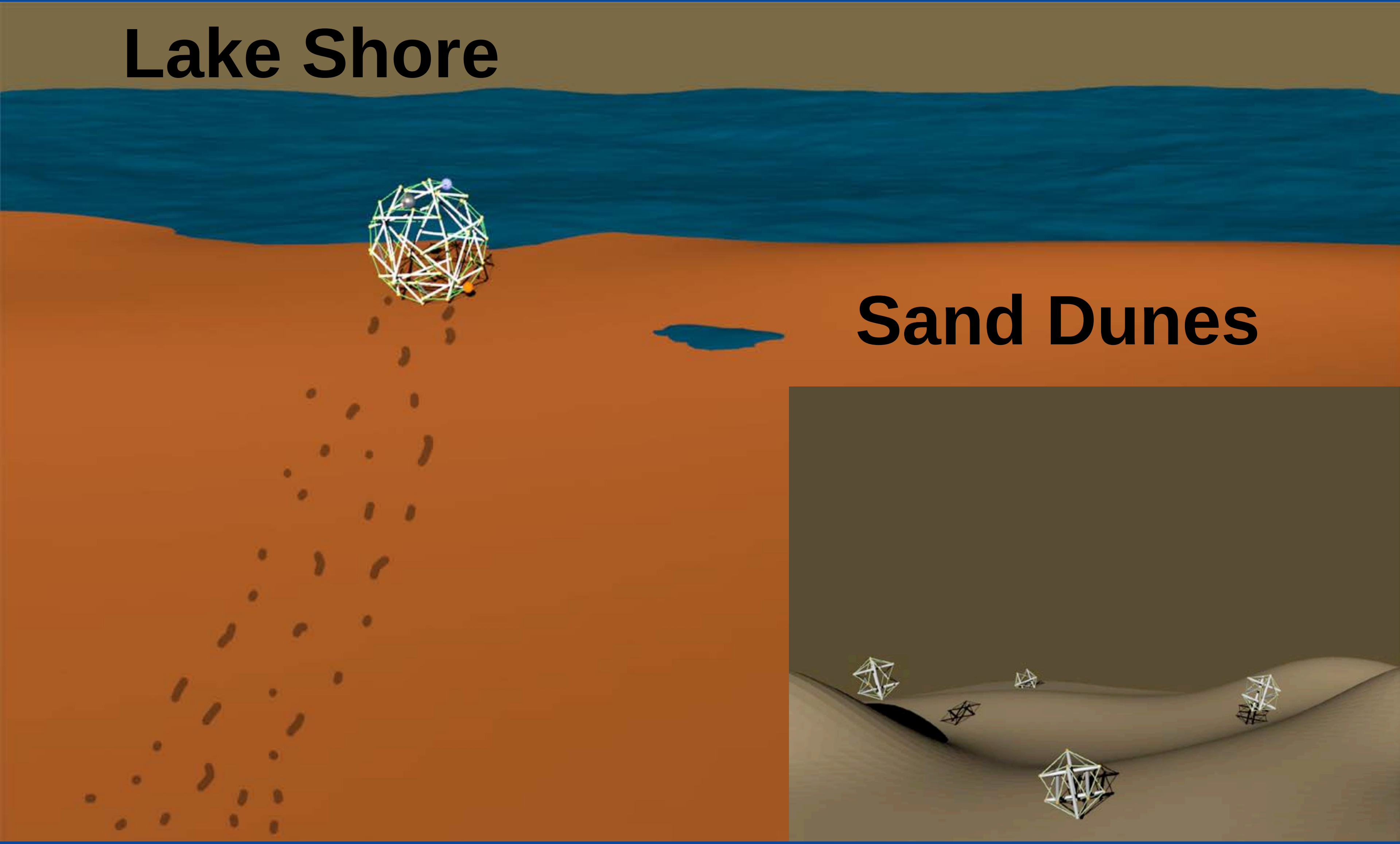
Obtain knowledge of the following as they relate to Titan:



- Distribution and composition of organics
- Organic chemical processes, their chemical context and energy sources
- Prebiological or protobiological chemistry
- Geological and geophysical processes and their evolution
- Atmospheric dynamics and meteorology
- Seasonal variations and interactions of the atmosphere and surface

Sources: NASA/JPL

Mission Scenarios



Instrumentation Overview:

The scientific payload for the Super Ball-bots mission will have three science packages:

Atmospheric and Meteorology Package:

- Temperature
- Methane Humidity
- Wind Speed
- Pressure

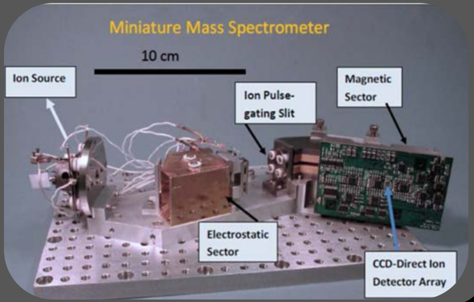
Mass: 2 kg

Analogous to the Titan Explorer MP3

Analytical Chemistry Package:

- Gas Chromatograph
- Mass Spectrometer

Mass: 2.8 kg



Imaging Package:

- Navigation Cameras
- Field Microscope

Mass: 1 kg

Analogous to the MER Microscopic Imager

Super Ball-bots Mission Options:

Small Vehicle:
- Atmos. & Met. Package
- Imaging Package

Estimated Mass: 40 kg

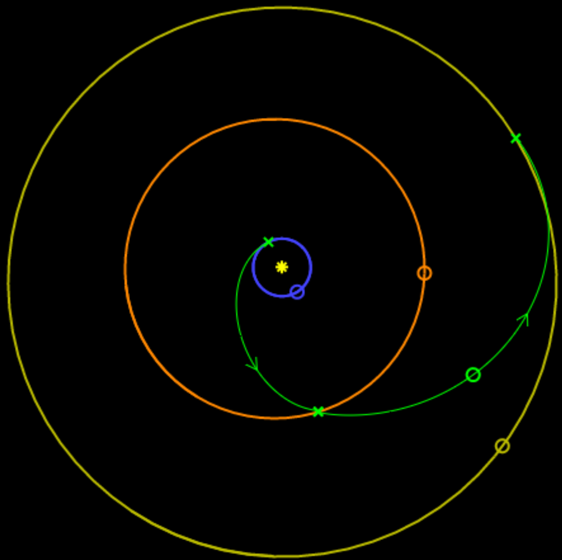
Large Vehicle:
- Atmos. & Met. Package
- Analytical Chem. Package
- Imaging Package

Estimated Mass: 75 kg w/ ASRG power source

Image Sources:
CSA, Brian Beard, JPL

Titan Trajectory planning

Baseline Trajectory to Saturn System



Saturn [Solar Sytem Exploration]

SPK-ID	6	Orbit Condition Code	0
Size	116464 km	Semi-major axis	9.577 AU
Eccentricity	0.051	Inclination	2.49°

Trajectory Itinerary

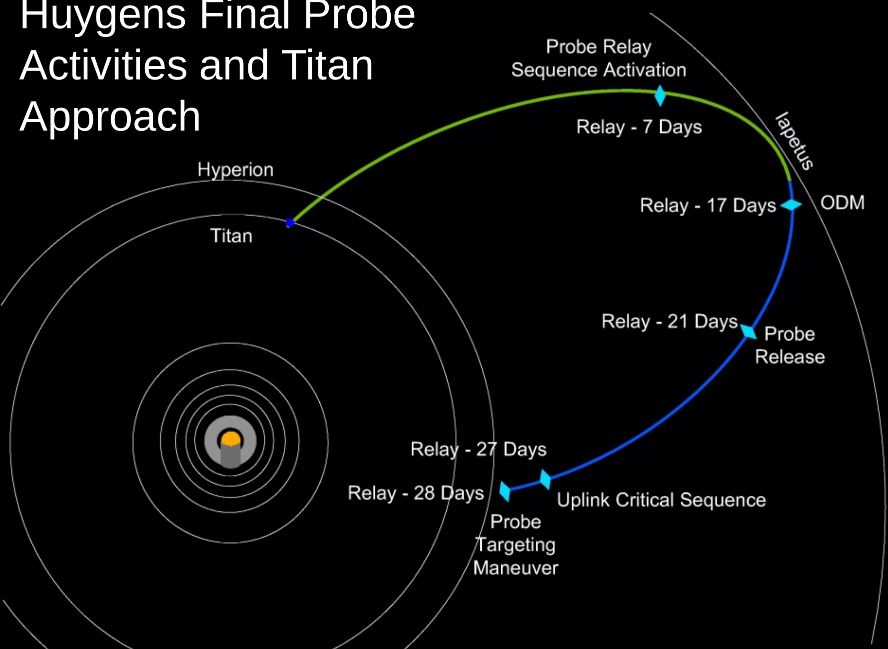
	Date	ΔV	
Earth Departure	Jan-18-2018	6.27 km/s	$C3 = 76.3\ km^2/s^2$ DLA = 1°
2.23-yr transfer			
Jupiter Flyby	Apr-13-2020	-	10.62 km/s relative speed 46.32 radii altitude
7.89-yr transfer			
Saturn Arrival	Mar-02-2028	75 m/s*	
10.12-yr total mission		76 m/s 6.35 km/s	post-injection ΔV total ΔV

Solar range: 0.98 - 9.46 AU Earth range: 0 - 10.44 AU

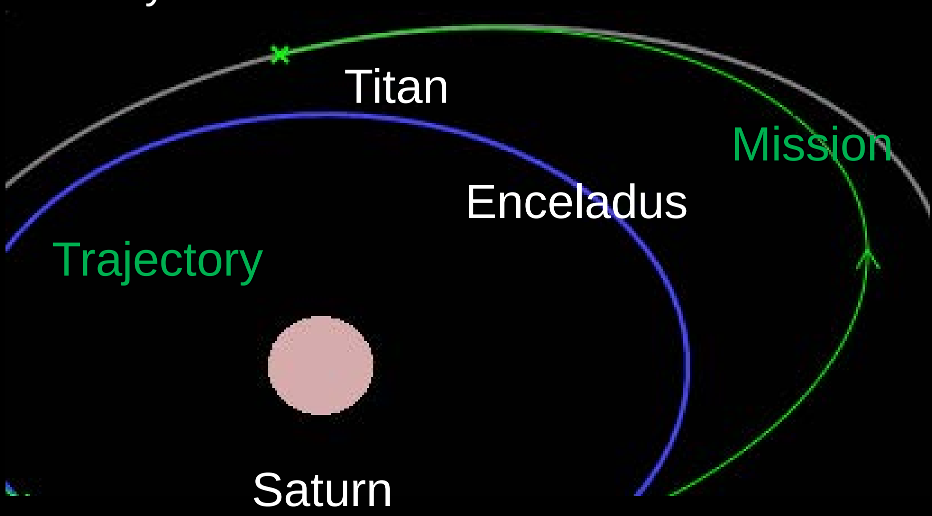
* ΔV to/from a $C3 = 0\ km^2/s^2$ local planetary orbit.

Source: Mission Design Center Trajectory Browser, Cyrus Foster

Huygens Final Probe Activities and Titan Approach



Potential Ball-bot Mission Trajectory utilizing semi-parallel approach vector and Titan velocity vector.



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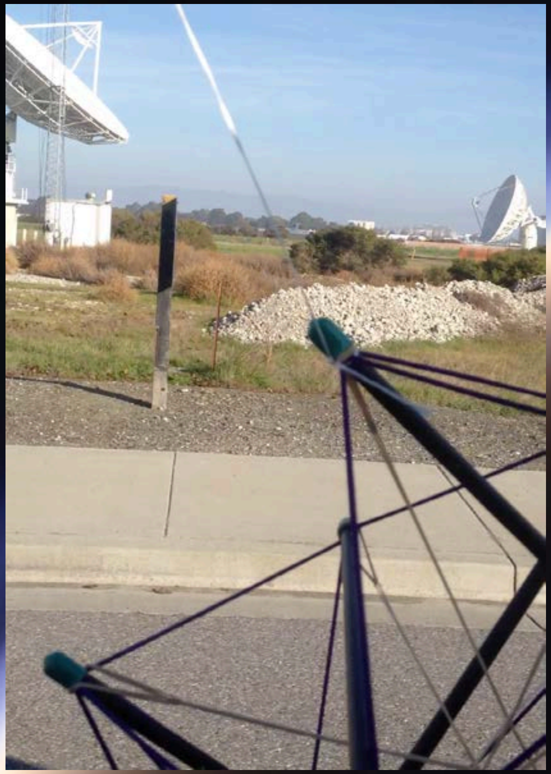
Unpacking for EDL

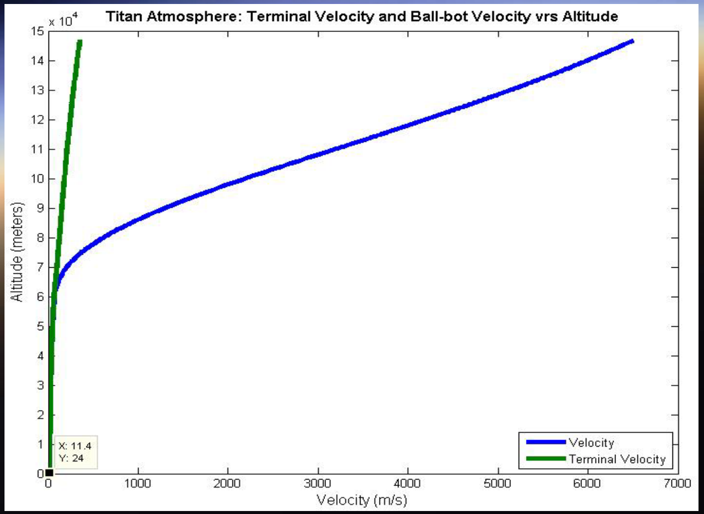
Drag Experiments for EDL

Earth



At 20 MPH
Average Angle: 44.6 degrees
Approximate Coefficient of Drag: 0.5

Titan



Super Ball-bot Entry Speeds:
•6.5 km/s @ 146 km alt. (similar to Huygens)

Dynamic Model:
Tensegrity payload sphere – diameter = .863 m
Constant coefficient of drag = 0.5
Vehicle Mass: 75 kg

Atmospheric Data:
Huygens HASI data 146.797 km to surface

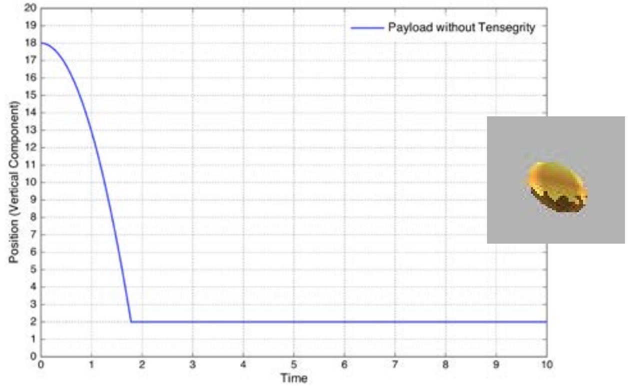
Impact Speed: 11.4 m/s (25.5 mph)
Huygens landed at 4.7 m/s

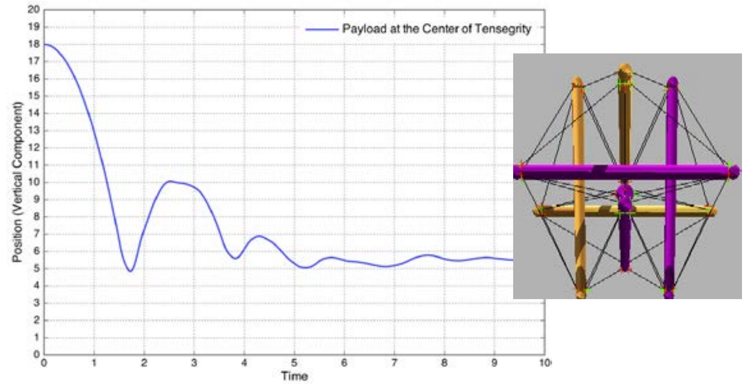
Simulated Landing Structure Tests

- **Tested Landing Performance at 15 m/s**

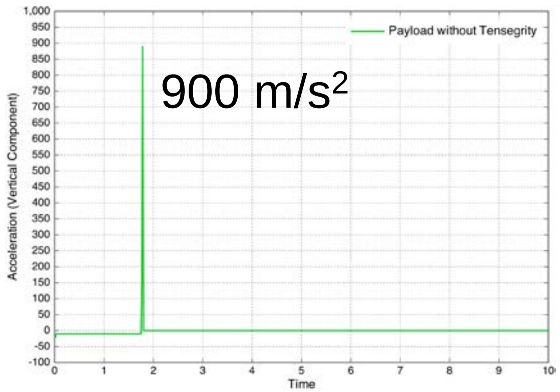
Payload (falling sphere) | Payload with Tensegrity

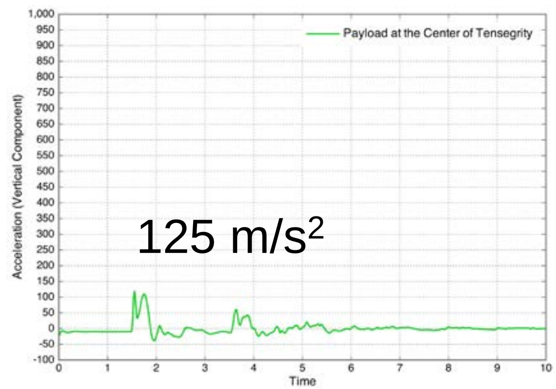
Position





Acceleration

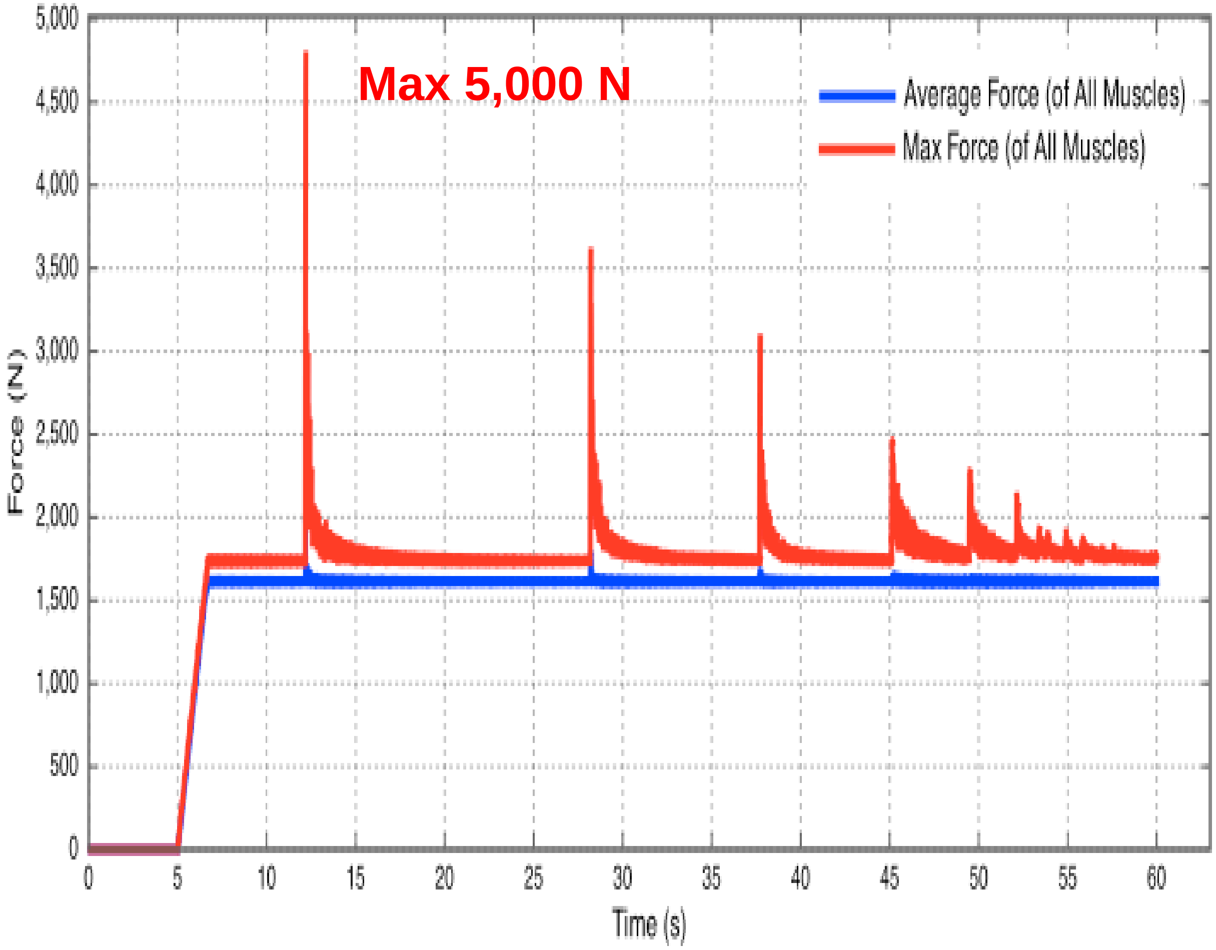




86% Reduction in Landing Forces With Tensegrity!

Payload experiences landing forces equivalent to 2.1 m/s (Huygens = 4.7 m/s)

Maximum Forces in Cables for 75kg Robot



Kevlar and Zylon used in MER parachute cables

Zylon rated at 5.8 GPa Tensile Strength

Zylon Cable with 1cm Diameter can handle **455,500 N**

Plenty of engineering tolerance

Constructing Prototype for Deployment and 10m Drop Test

Terrestrial
Drop Test Landing Speeds:

$$v_i = \sqrt{2gd}$$

g = 9.8 m/s^2
d = 10 m

v = 14 m/s

Expected Landing Speed on Titan = 11 m/s

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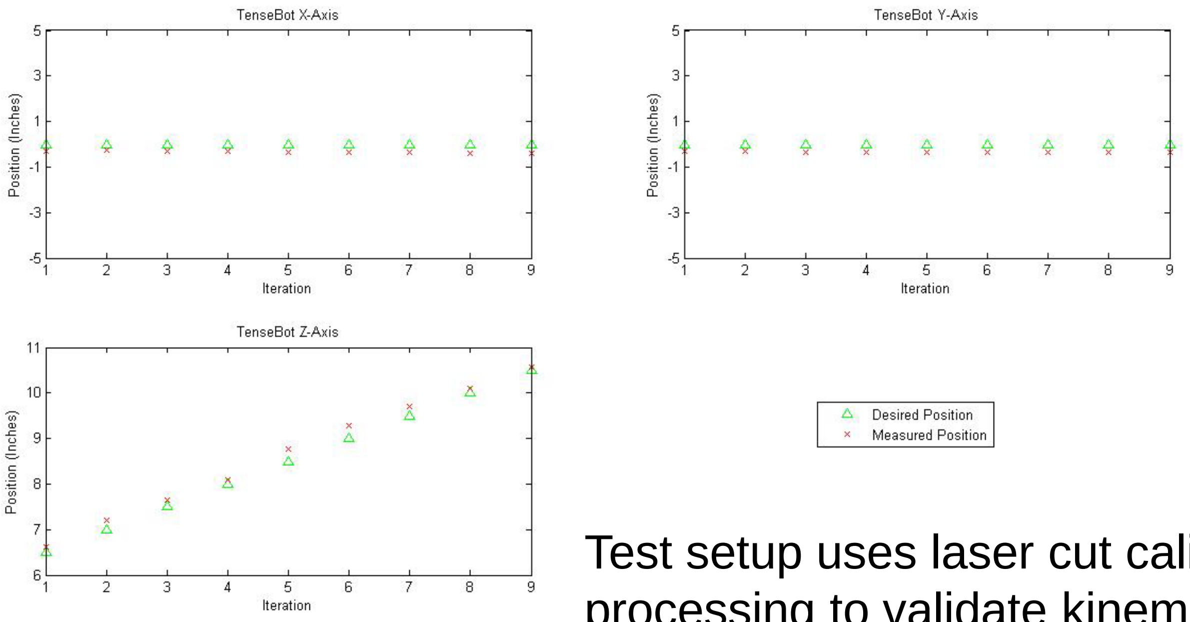
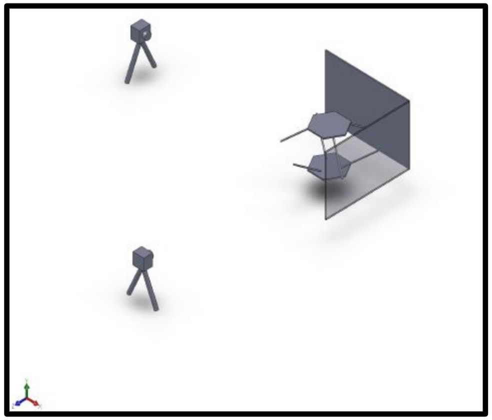
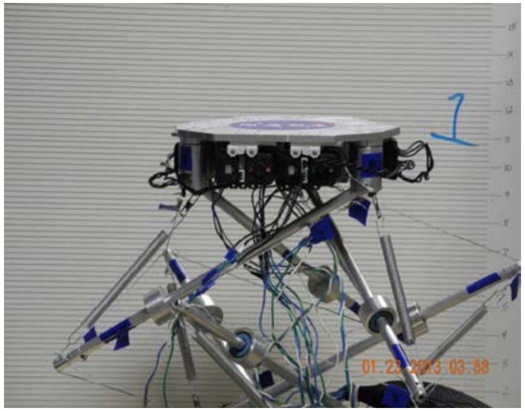
Develop and Test Forward and Inverse Kinematics

o Kinematics Difficult due to integrated forces and positions in tensegrity structure
o Implemented numerical algorithm
o Tested and verified on prototype robot







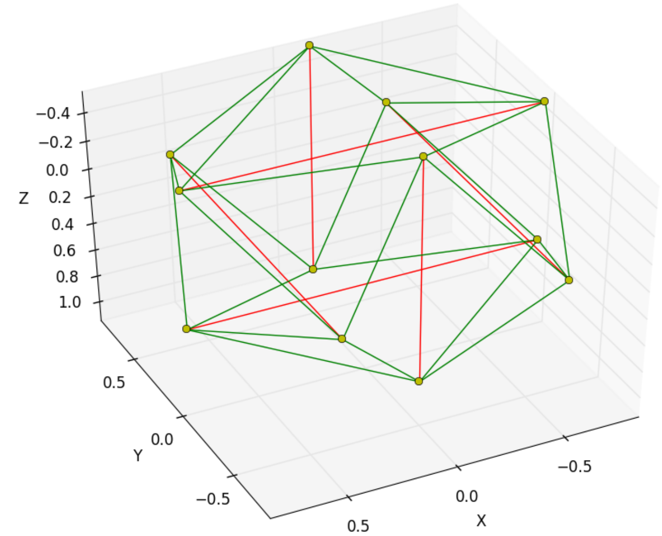
Test setup uses laser cut calibration board and image processing to validate kinematic algorithms on robot.

Super Ball Bot Mobility Forces Simulation

Used Two Different Analysis methods:

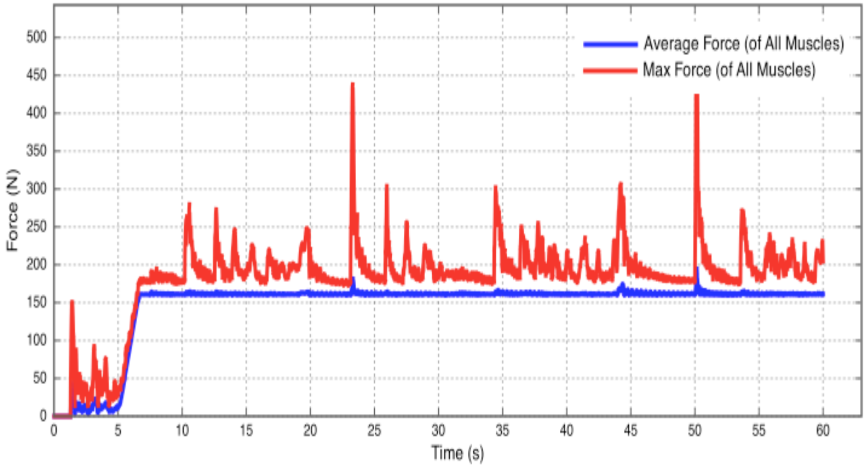
o Physics Simulation

o Euler-Lagrangian formula developed by Skelton[1]



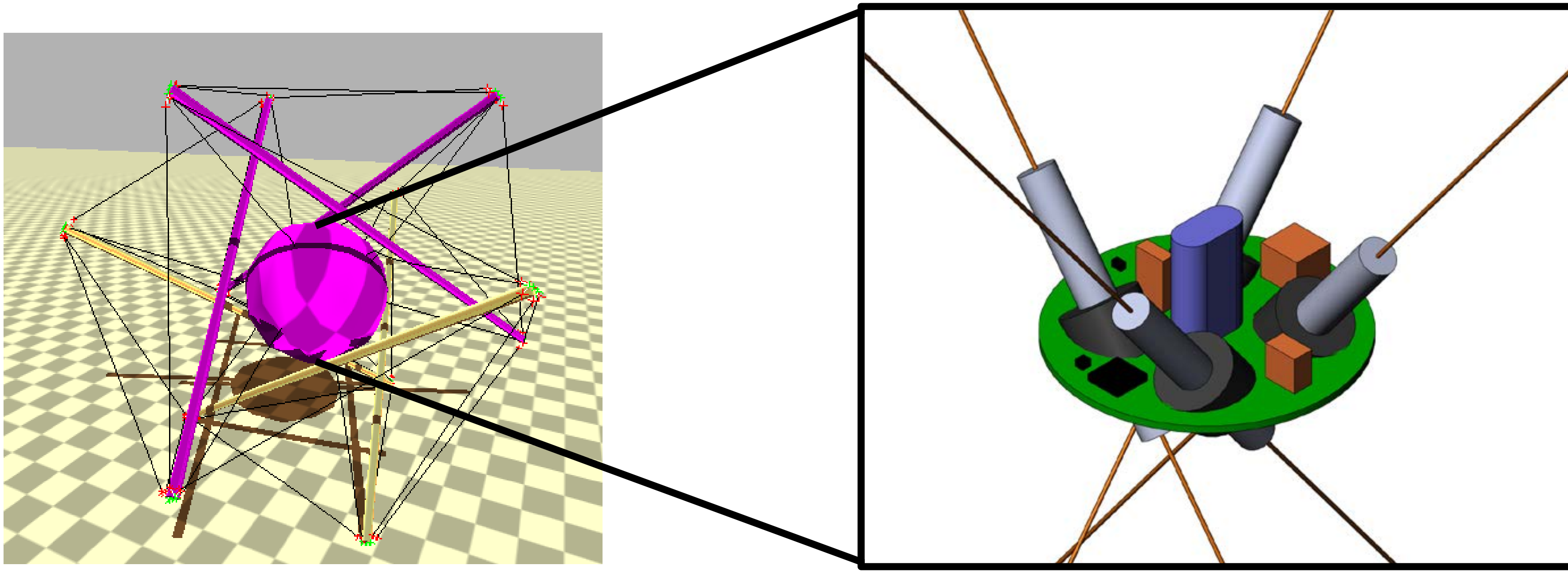
o Results depends on Level of Pre-stress (i.e. overall stiffness)

o 500N Actuators Required



1: Sultan, C., Corless, M., & Skelton, R. E. (2002). Linear dynamics of tensegrity structures. Engineering

Payload Based Actuation



- Fewer Actuators
- Actuators located in shock absorbed payload structure
- Simplified wiring for power and control

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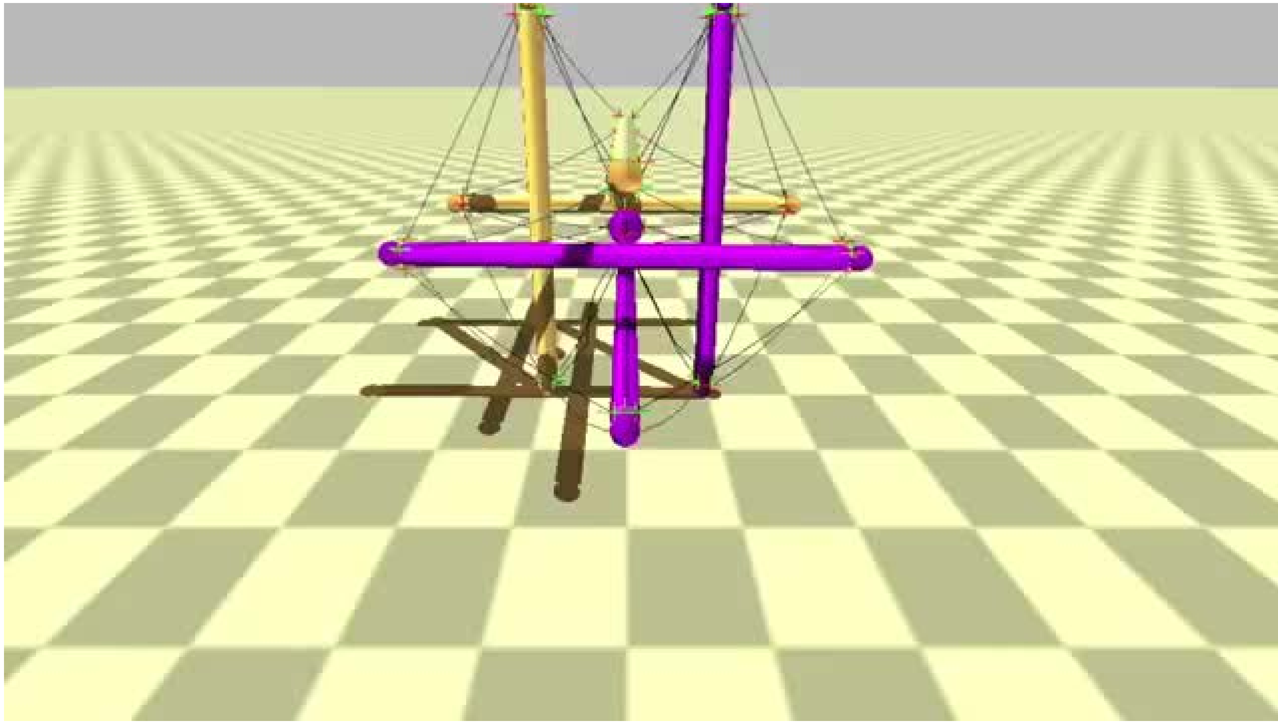
Learning Control Algorithms



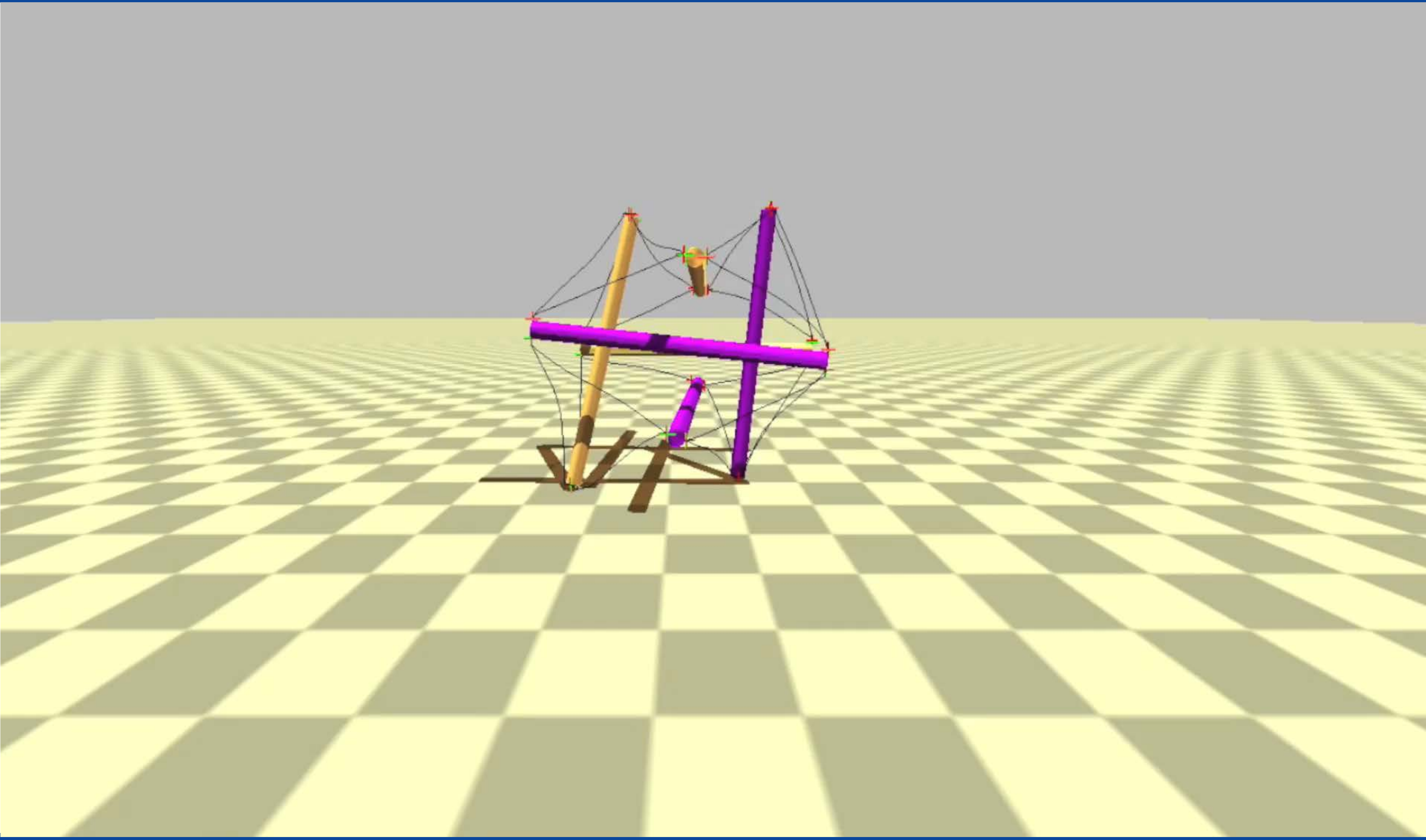
Difficult to control with traditional methods

- High Degree of Freedom
- Nonlinear
- Oscillatory

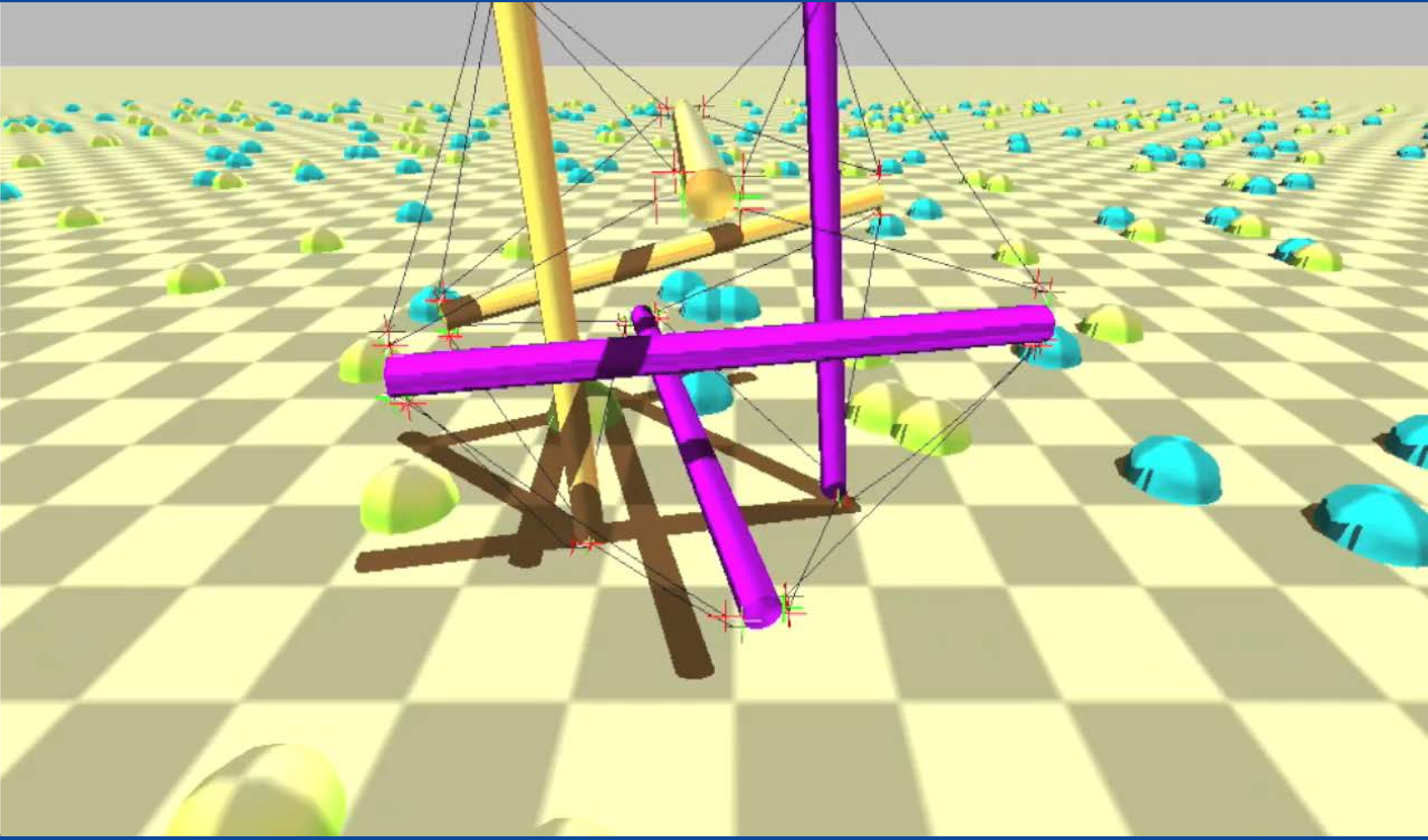
Alternative: Evolve Control

- Start with initial population of control policies
- Test performance in simulator
- Remove poor control policies and replicate better ones
- Evolve high performance population

Robust Against Failures



Can Evolve for Many Environments



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Collaborations and Students

Collaborations:	**Students Involved**
- U. C. Santa Cruz	- 1 PhD, 1 Masters
- University of Idaho	- 2 Masters, 6 Undergrad
- U. C. Berkeley	- 1 PhD, 7 Undergrads
- Oregon State	- 1 PhD
- Case Western Reserve	- 1 PhD

International Collaborations (Donated Fundamental Research)

- EPFL (Switzerland)	- 1 Master Student
- Ghent University (Belgium)	- 1 PhD Student, 3 Undergraduates
- KAIST (Korea)	- 1 Post Doc

Total: 26 Students Involved in NIAC project

PR and Publications

TIME
TECHLAND

What's Next for NASA? 10 Wild Newly Funded Projects

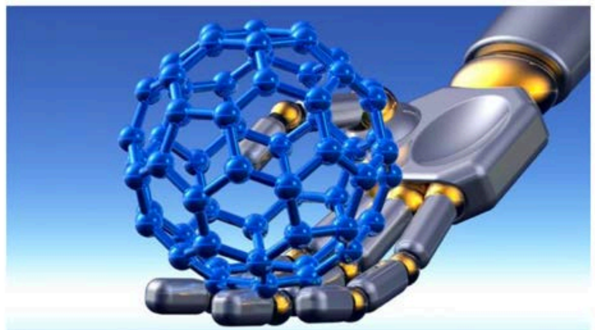
BBC
FUTURE

SPACE STATION | 3 February 2013

Nasa's 'crazy' robot lab

Richard Hollingham

Science & Environment | Mars | Technology | Design | Engineering | Robot



(Copyright: SPL)

Inside a laboratory in California, space engineers are designing a new generation of rover... and they look like nothing you have seen before.

TECH BUZZER
Latest Technology News and Reviews

"Not actually crazy. But certainly innovative and ambitious."

Papers:
2 Accepted for Publication (AAMAS Conf., ARMS Workshop)
1 Submitted for Review (GECCO Conferences)
1 Being Prepared for Planetary Probes Workshops.
1 Masters Thesis Completed.

GECCO
AAMAS 2013
IPPW

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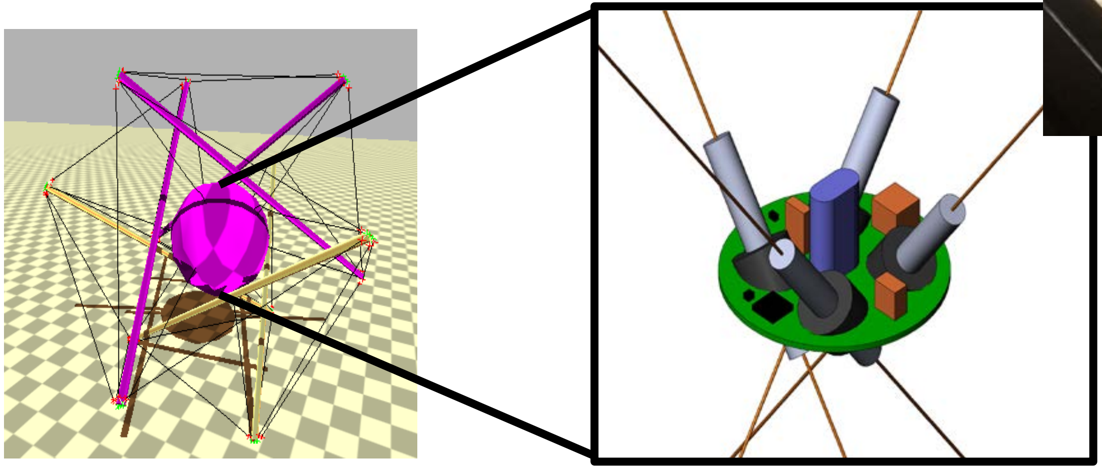
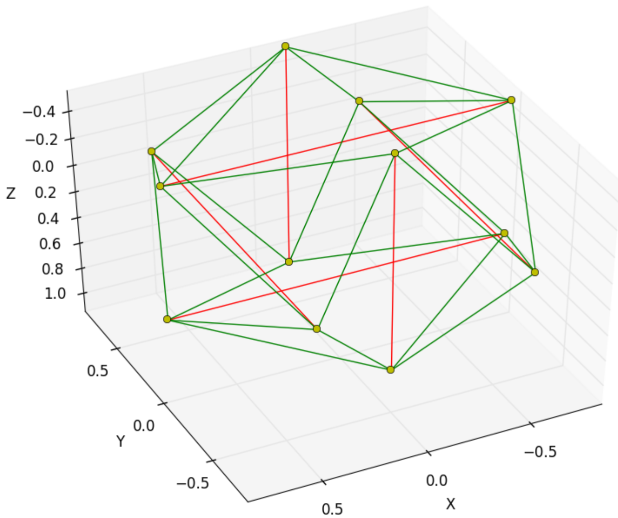
EDL and Mobility Engineering

- Test Deployment Prototype
- EDL Drop Tests

- Design Mobility Prototype (Construction and Testing in Phase 2)



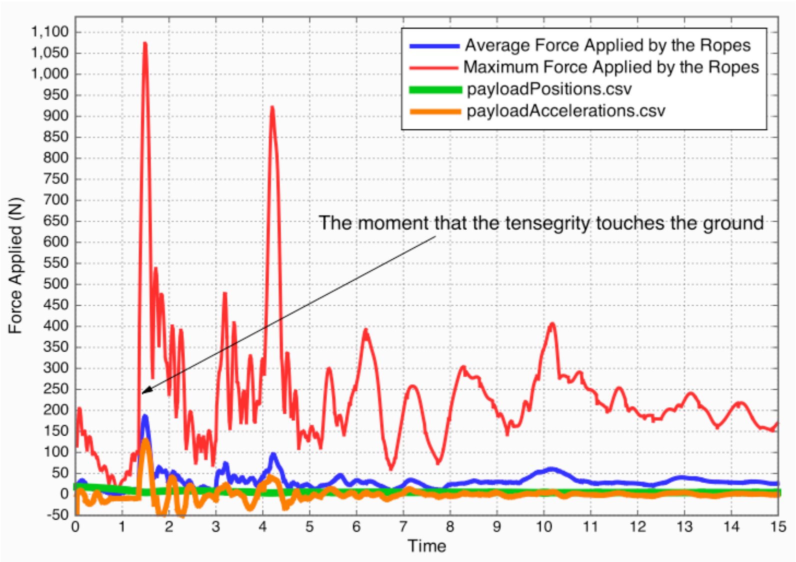
Further Mission Design



•Use models to refine mission engineering

•Calibrate Models with Prototype tests

•Improve physics simulations with mission relevant cables and material properties.



Central Pattern Generators for Mobility Control

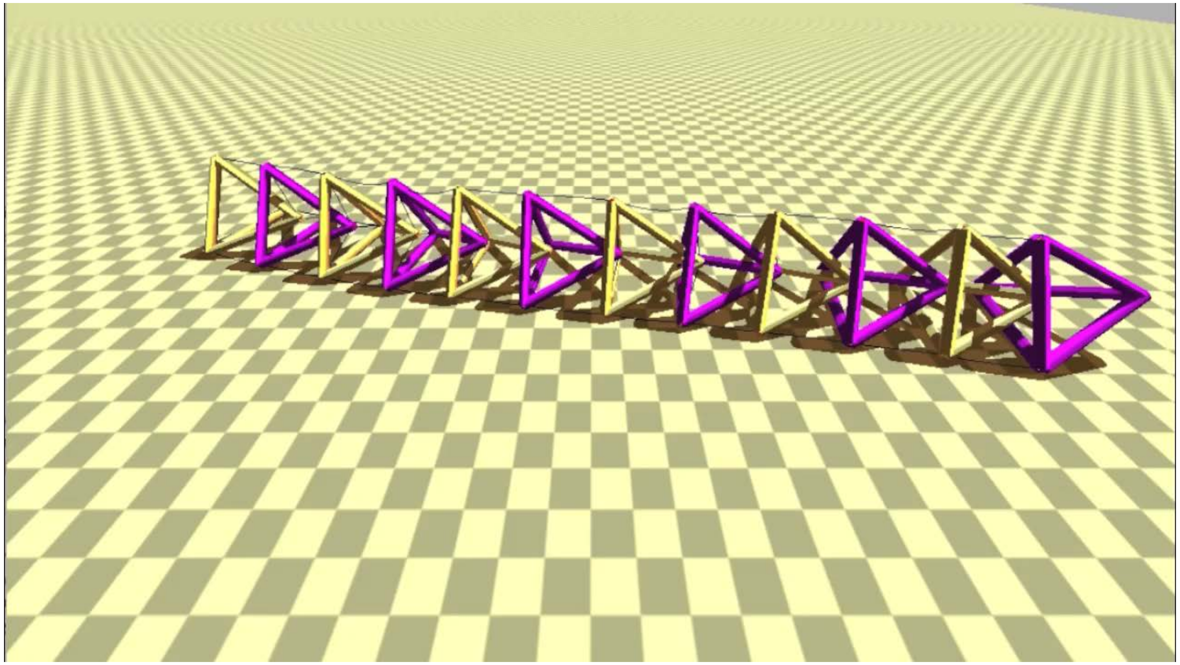
Central Pattern Generators (CPG's) are Neuro-Circuits involved in animal motion control

Our Research Shows:

•Ideal for control of Tensegrity Robots

•Create gaits that are robust to terrain variations

•Provide reactive reliability for unplanned events



Will port CPG controls from other projects to SuperBall Bot

Questions?

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Vytas SunSpiral
(Stinger Ghaffarian Technologies)
David Atkinson
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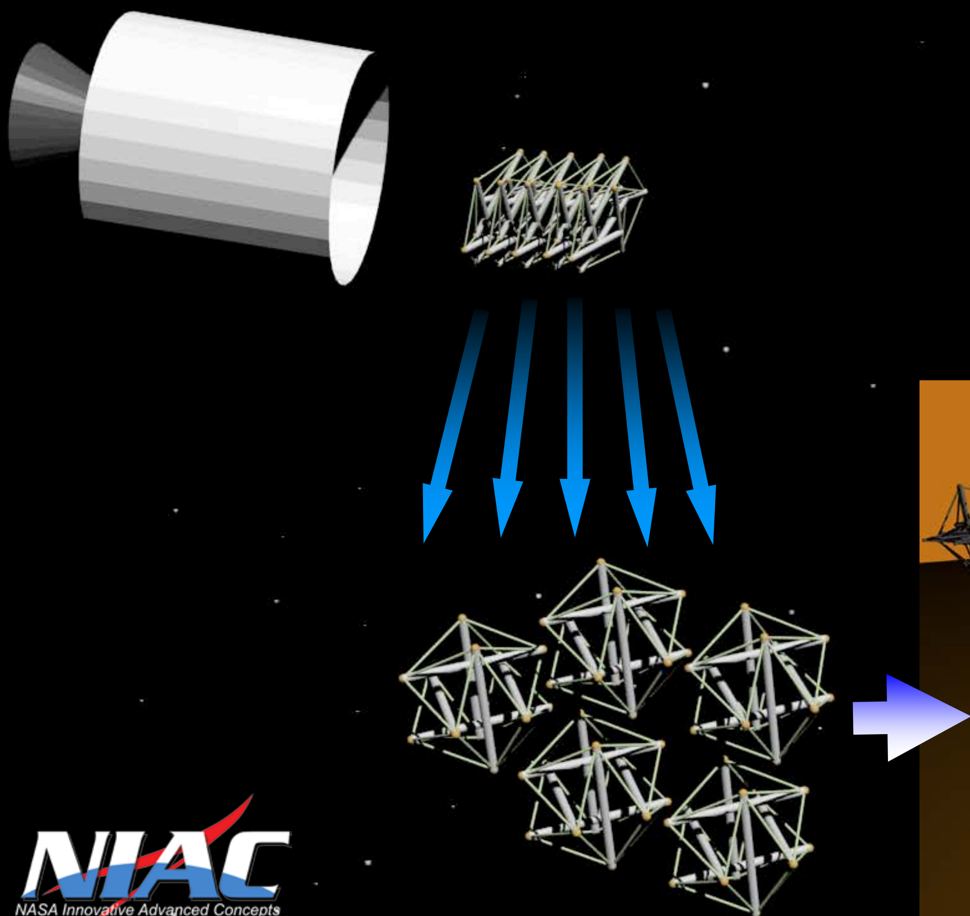
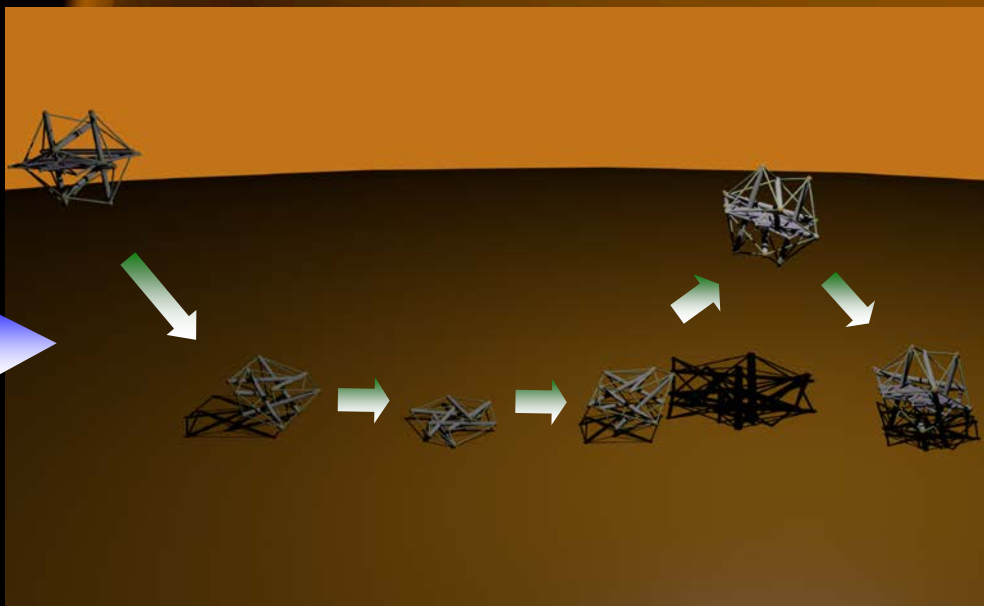
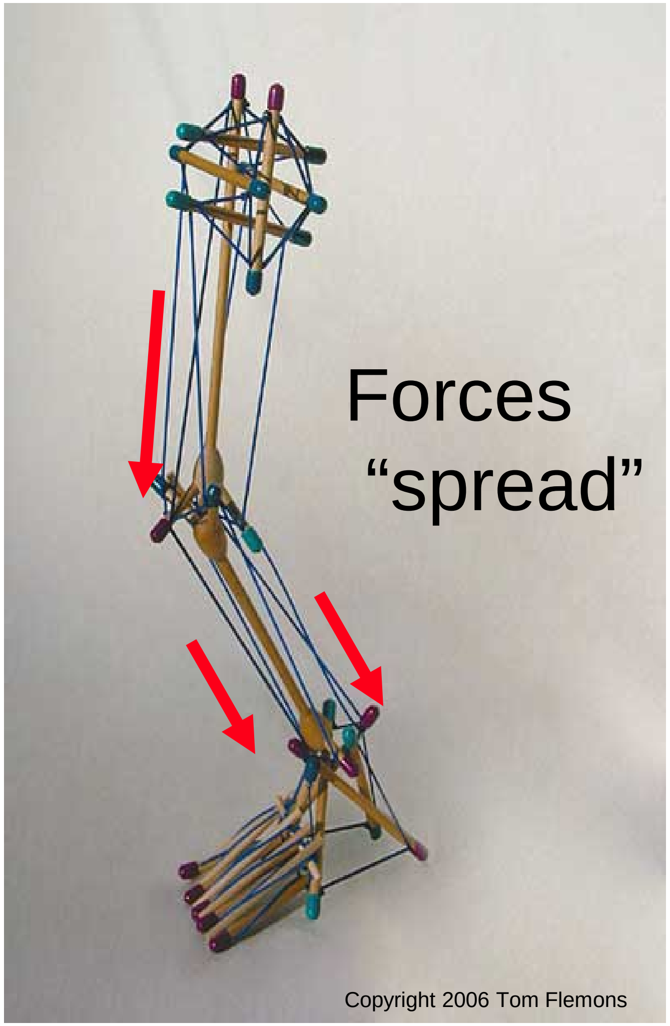


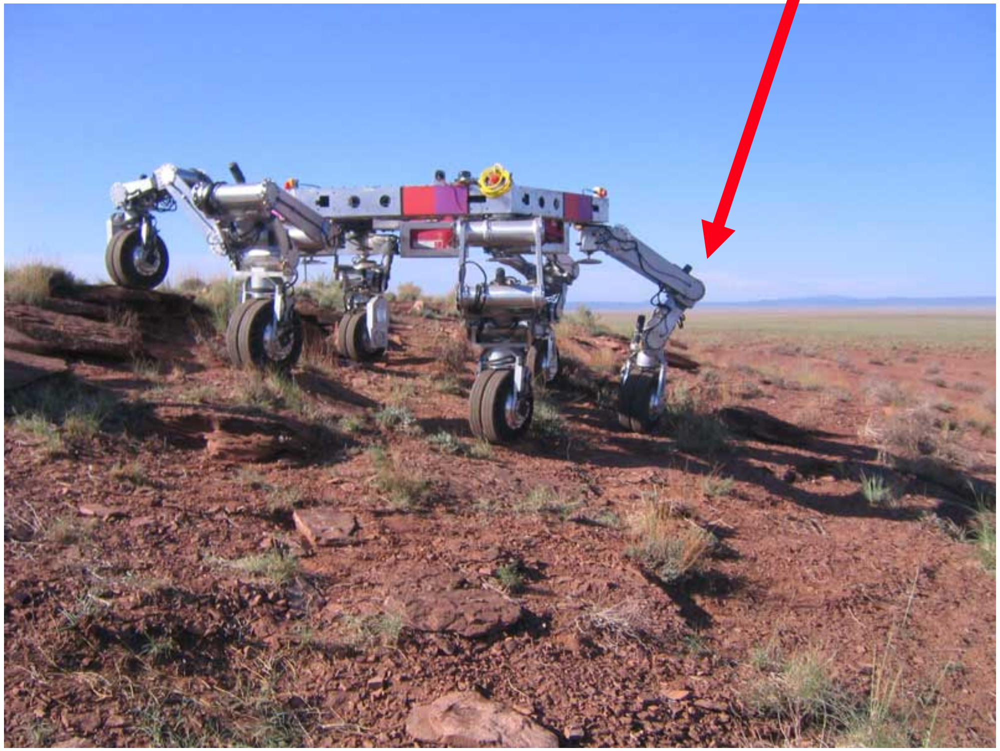


NIAC
NASA Innovative Advanced Concepts

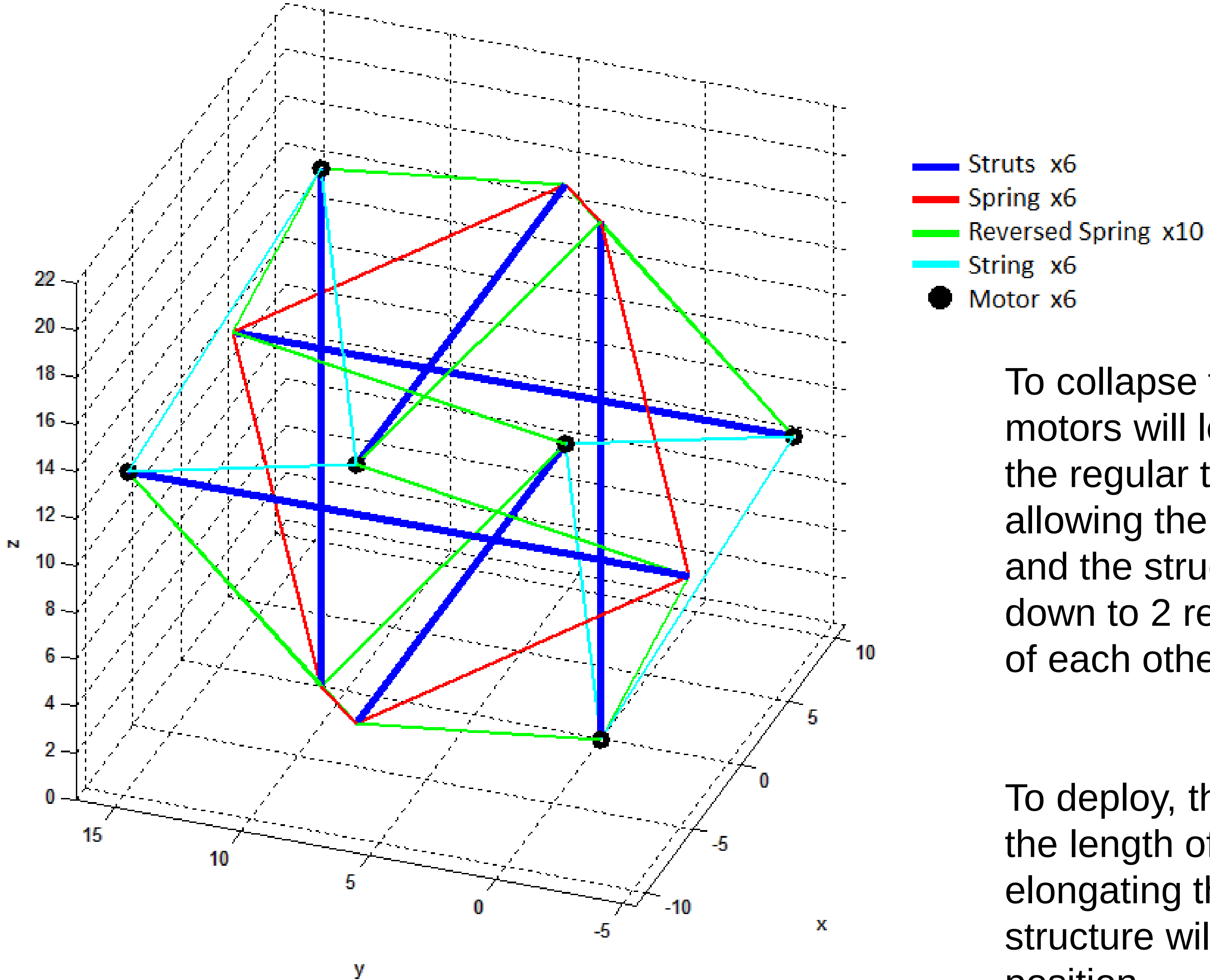
Tensegrity Ideal for Robotics



Forces Accumulate
in Single Joint



Structure Design – Home Position



x12

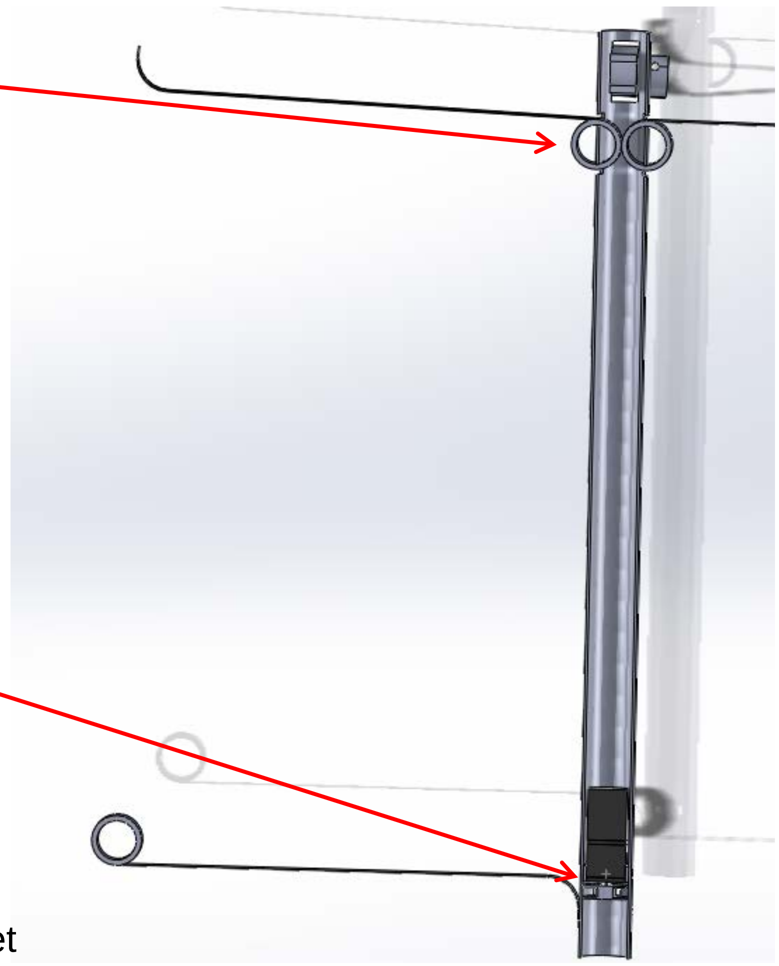
To collapse the structure the motors will lengthen the strings of the regular triangles they create, allowing the springs to contract and the structure to collapse down to 2 regular triangles on top of each other

To deploy, the motors will shorten the length of the strings, elongating the springs, and the structure will resume its home position

Structural Components

4.95 lb constant force springs provide passive tension for deployment

172:1 geared motor with 48 CPR Encoder mounted with a press-fit sleeve around the gear box and set screws attaching it to the frame



- **Only 6 actuated Strings required for Deployment.**
- **Possible to do with only two actuators.**

SuperBall Bot Prototypes (just starting)

U. Idaho Structural Analysis & Drop Tests

CaseWestern Shape Change Project Actuators Inside Rods